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## *in relation to Ontario's policy directions for emulating natural disturbance*

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# Abstract

This study focused on assessing distribution of fire sizes and their spatial proximity of occurrence as relevant to directions in Ontario's *Forest Management Guide for Natural Disturbance Pattern Emulation* (NDPE guide). Given the many inadequacies of estimating fire regime characteristics by empirical data of fire history, we used a simulation modelling approach for this assessment. We used BFOLDS, which models fire disturbances mechanistically and forest succession empirically, to simulate fire regime scenarios for boreal Ontario. The study area encompassed the ecoregions 3E, 3W, 3S, 4W, and 4S, in which fire regimes were simulated for 200 years. We used three potential fire weather scenarios, normal, cold, and warm, and two possible lightning patterns, random and biased, as model assumptions to address uncertainties in knowledge of long-term climate and weather patterns. All simulation scenarios were replicated to capture stochastic variability that emerges during modelling. From these results, we extracted fire size distributions and probabilities of spatial occurrence of fires for each simulation scenario. Fire size distribution varied significantly among ecoregions: some were characterized by relatively few small fires while others were dominated by many large fires. Effects of weather scenarios and lightning patterns were not consistent: in some ecoregions significantly higher number of larger fires resulted under the warm fire weather scenario, and for the biased lightning pattern; in others differences were not significant. Spatial proximity of fire occurrence varied significantly among all ecoregions, as well as fire weather scenarios, but not between ignition patterns. Overall, more fires occurred in the proximity of others under warm fire weather. The NDPE guide's direction for forest harvest sizes matched the simulated fire size distribution in only two ecoregions, under specific fire weather and lightning pattern scenarios. The guide's direction overestimated the fire size distribution in the same two ecoregions under other specific weather–lightning pattern scenarios. In the other three ecoregions, it underestimated fire size distribution under all simulation scenarios. The guide's direction for spatial proximity was not congruent with results from any simulated scenario in any ecoregion. However, the probability of spatial proximity was low in all but one ecoregion. In addition to the assessment of NDPE guide's direction, this study demonstrates that fire size distributions appear to be unique to ecoregions, and that these can vary further if the fire weather conditions change.

# Acknowledgements

We thank Phil Elkie, Michael Gluck, and Rob Luik for providing various databases, which were essential for this simulation study; Joe Churcher, Phil Elkie, Michael Gluck, and John McNicol for clarifying the directions contained in the *Forest Management Guide for Natural Disturbance Pattern Emulation*; Lisa Buse, Joe Churcher, John McNicol, and three anonymous reviewers for their constructive comments on draft report, which helped to improve its clarity.

# Resumé

Cette étude vise avant tout à évaluer la distribution par taille des feux de forêt et leur proximité spatiale par rapport aux directives énoncées dans le *Forest Management Guide for Natural Disturbance Pattern Emulation* (Guide de gestion forestière pour la reproduction de perturbations naturelles, guide NDPE) de l'Ontario. Étant donné les nombreuses faiblesses de l'évaluation des caractéristiques des régimes de feux à partir de données empiriques tirées de l'historique des feux, nous avons choisi de suivre plutôt une démarche de modélisation par simulation pour mener l'étude. Nous avons utilisé le système BFOLDS, qui permet de produire mécaniquement des modèles de feux et empiriquement des modèles de succession des forêts afin de simuler les régimes de feux des forêts boréales de l'Ontario. L'étude est menée sur les écorégions 3E, 3W, 3S, 4W et 4S, où des régimes de feux sont simulés depuis 200 ans. Nous nous sommes fondés sur trois conditions météorologiques propices aux incendies forestiers (normal, froid et chaud) et deux modèles d'éclairs (aléatoire et biaisé), à titre de postulats, pour combler les carences en connaissances sur les régimes climatiques et météorologiques à long terme. Tous les scénarios de simulation ont été répliqués pour recueillir toutes les variables aléatoires obtenues durant le processus de modélisation. Nous avons pu déterminer à partir des résultats de chaque scénario les distributions par taille et les probabilités de survenue spatiale des feux de forêt. La distribution par taille des feux diffère beaucoup d'une écorégion à l'autre : certaines écorégions étaient caractérisées par un petit nombre de petits feux et d'autres, par un grand nombre de grands feux. Les résultats relatifs aux différents scénarios météorologiques et modèles d'éclairs étaient peu cohérents : certaines écorégions étaient caractérisées par un plus grand nombre de grands feux par temps chaud que par temps froid, et de modèles biaisés d'éclairs que de modèles aléatoires; dans d'autres régions, les différences étaient peu importantes. La proximité spatiale des feux diffère de façon importante d'une écorégion à l'autre, tout comme les modèles de conditions météorologiques propices aux incendies forestiers; les modèles d'allumage ne diffèrent toutefois pas. Dans l'ensemble, plus de feux éclatent à proximité d'autres par temps chaud. Les énoncés sur les superficies de récolte forestière du guide NDPE correspondent à la distribution par taille des feux simulée dans seulement deux écorégions, conformément à des scénarios de météo-incendie et à modèles d'éclairs précis. Le guide surévalue la distribution par taille des feux dans ces deux mêmes écorégions quand on prend en compte d'autres scénarios météorologiques et d'éclair. Dans les trois autres écorégions, le guide sous-évalue la distribution par taille lorsque l'on prend en considération tous les scénarios de simulation. Les directives sur la proximité spatiale du guide n'étaient pas en harmonie avec les résultats des scénarios de simulation utilisés pour chaque écorégion. Cependant, les probabilités de proximité spatiale étaient faibles dans toutes les écorégions sauf une. En plus de l'évaluation des directives du guide NDPE, l'étude montre que les distributions par taille des feux semblent être propres aux écorégions, et ces distributions peuvent varier encore plus lorsque les conditions météorologiques propices aux feux forestiers changent.

# Contents

# Introduction

It is generally accepted that frequent stand-replacing fires are an inherent characteristic of boreal forest landscapes (Heinselman 1973, Rowe and Scotter 1973). Therefore, attempts to emulate natural disturbances as a forest management goal in boreal landscapes consider the natural fire regime as the major benchmark. In Ontario's case, emulating natural forest disturbances is a principle in the *Crown Forest Sustainability Act* (Statutes of Ontario 1995), which led to the development of forest management policies that guide forest harvest practices based on natural disturbance patterns. The *Forest Management Guide for Natural Disturbance Pattern Emulation* (NDPE guide, OMNR 2001), applied in Ontario since 2003, specifies directions and provides standards and guidance to emulate fire disturbances during forest harvest. A key aspect of this guide is directing forest harvest patch patterns with respect to their size distribution and spatio-temporal juxtaposition.

In 2003, the Ontario Ministry of Natural Resources (MNR) was required to assess the effectiveness of the directions provided in the NDPE guide (Condition 39c of the Declaration Order MNR-71 (OEAB 2003) under the *Environmental Assessment Act*). Under this mandate, a series of multi-scale scientific studies (detailed by Perera and Buse 2006) was initiated in 2005 to improve the understanding of characteristics of natural fire regimes in Ontario's fire-driven landscapes. One aspect of these studies was to examine and reduce the uncertainties associated with the NDPE guide directions for forest harvest patch size distribution and spatio-temporal proximity.

As a first step in reducing these uncertainties, we documented the state of published knowledge about fire size distribution in boreal forests of North America (Cui and Perera 2008). No published reports were found on spatio-temporal proximity of fires, and the state of knowledge of that aspect of forest fire regime appeared non-existent. From the review of literature, it was evident that most information on fire sizes in boreal forests is derived from empirical studies of fire histories, and therefore the inferences may be restricted by limitations of sample sizes. Theoretically, fire sizes are expected to follow power law distribution, with the specific properties of the distributions subject to vary with an array of environmental factors as well as anthropogenic influences. Therefore, fire size distributions appear to be spatially unique, as determined by local geo-climate and fuel patterns that influence fire occurrence and behaviour, and may change if climatic conditions change. All these factors make fire size distribution highly variable, which must be considered in its assessment. However complete and accurate, empirical fire history data represent but one of many possible realizations of nature and therefore cannot provide any indication of spatio-temporal variability and stochasticity associated with a highly complex process such as forest fire. Under such uncertainties and complexities, simulation modelling provides a useful tool to explore fire regime characteristics (Cary et al. 2006).

## Goal of this report

By understanding the potential variability of forest fire size distribution and spatial proximity of fires in Ontario's boreal fire regime under natural conditions, forest policymakers can provide better strategic guidance to help forest managers emulate natural patterns of fire disturbance during forest harvesting. Thus, the broad goal of the study reported here was to explore the long-term variability of Ontario's boreal forest fire regime using a simulation model, based on an ecoregional stratification that addresses the spatial variability of geo-climate of boreal Ontario.

Specifically, we examine the characteristics of fire size distribution and the spatial proximity of fire occurrence across ecoregions 3E, 3W, 3S, 4S, and 4W (adapted from Hills 1959), as well as in relation to assumptions of fire weather changes. We included fire weather scenarios to represent possible changes in climate in each ecoregion and their possible effects on fire. Subsequently, we relate these results to the directions for harvest patterns provided in Ontario's NDPE guide by answering two specific questions: Does $80^{th}$ percentile of cumulative fire size distributions equal 260 ha?; and Do new fires occur within 200 m of a fire that is less than 20 years old?

# Methods

## Study area

For this simulation modelling exercise, the study area included Ontario's managed boreal forest region and the western part of its Great Lakes–St. Lawrence transitional zone (Rowe 1972), which is dominated by black spruce (*Picea mariana* [Mill.] B.S.P.), jack pine (*Pinus banksiana* Lamb.), trembling aspen (*Populus tremuloides* Michx.), birch (*Betula* spp.), and balsam fir (*Abies balsamea* [L.] Mill.), with significant red pine (*Pinus resinosa* Ait.) and white pine (*Pinus strobus* L.) components in the more southern parts.

Its land base is predominantly Crown land, managed extensively for timber and other values and much of it has been harvested at least once during the past century. As shown by Gluck and Rempel (1996) in the northwestern boreal forest, periodic revisions of provincial forest harvest policies have created distinctly different landscape patterns. Since 2003, directions for forest harvest patterns in Ontario's boreal forest are provided in the *Forest Management Guide for Natural Disturbance Pattern Emulation* (NDPE guide, OMNR 2001). This guide is expected to be replaced by a comprehensive guide that will support biodiversity conservation at multiple scales, by directing forest harvest patterns, forest composition, as well as habitat supply and conservation efforts (http://www.mnr.gov.on.ca/en/Business/Forests/2ColumnSubPage/STEL02_164533.html). Many disturbance regimes affect the boreal forest landscape of Ontario. While the primary disturbance regime is stand-replacing fires, other natural causes of periodic disturbances such as insect epidemics and blowdown are also common. This area has been disturbed heavily by periodic fires (both lightning and anthropogenic) during the last century (Perera et al. 1998).

The study area has been divided into hierarchical strata of site regions and nested site districts by Hills (1959) based on its geo-climatic patterns. Since Hills' classification, many attempts have been made to modify this ecoregional framework and produce many cartographic products, but the major groupings have not changed considerably (Baldwin et al. 1998). These ecoregional strata have been used widely as surrogate units for developing strategic land use plans (e.g., parks and protected area design) as well as policies (e.g., new provincial forest policy guides). We used the major ecoregions in boreal Ontario, namely 3E, 3W, 3S, and 4S, as well as 4W, which falls within the western transitional zone of boreal forest (Figure 1). The cartographic units follow the 2002 version of Ontario's ecoregion map (http://www.mnr.gov.on.ca/MNR_E005108.pdf, p. 77).

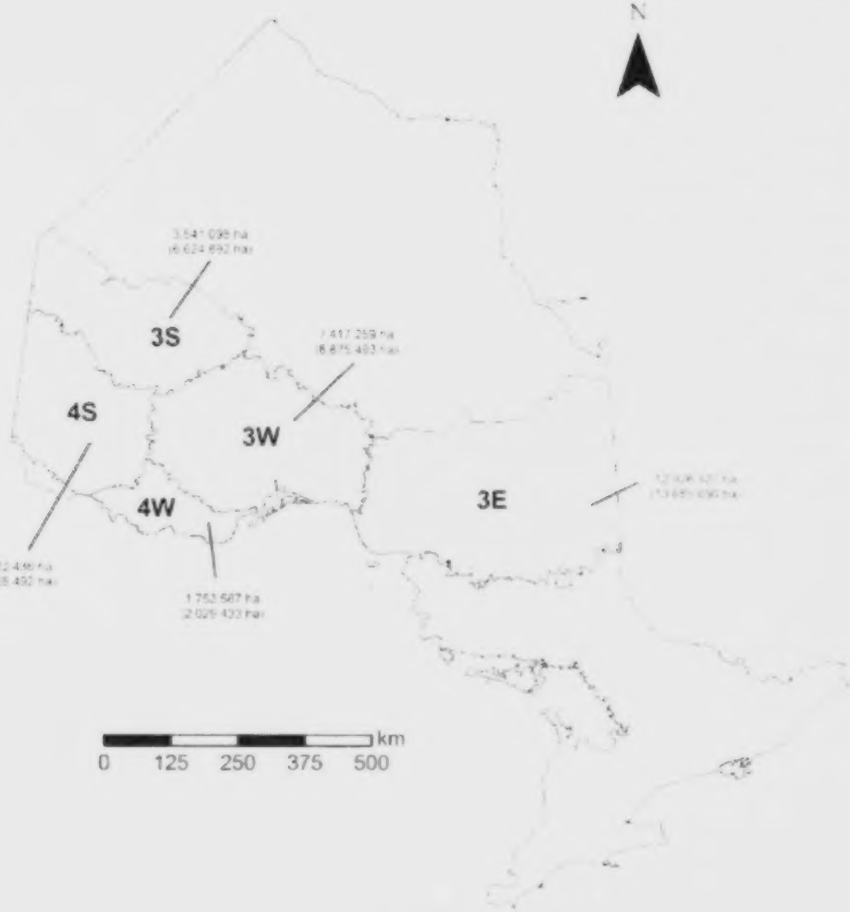


*Figure 1. The study area and its ecoregions, which follow 2002 version of Ontario's ecoregion map (http://www.mnr.gov.on.ca/MNR_E005108.pdf, p. 77), with their forested extent (and total area).*

## Simulation model

We used the Boreal Forest Landscape Dynamics Simulator (BFOLDS) to model the fire regime of the study area. BFOLDS is a spatially explicit model that simulates multiple fire events in a very large area over time and subsequent forest cover succession trajectories. In addition, it models the forest cover changes due to ageing, in the absence of stand-replacing fire events. BFOLDS simulates forest fire events using a process-based fire simulation module, allowing for mechanistic processes of fire ignition, fire spread, and fire event extinguishment to occur as a function of fire weather, topography, and fuel patterns. Its raster-based fire growth module is founded on the principles of the Canadian Fire Behaviour Prediction system (FBP) (Forestry Canada Fire Danger Group 1992), and BFOLDS simulates multiple fire events on a given landscape at 1 ha resolution and continuously in time, using spatial data on fuel types, weather, and topography. As well, it is a stochastic simulation model, designed to capture the probabilities associated with sub-processes of fire regimes such as forest cover transition and subsequent fuel availability. In the model, long-term forest succession is stochastically simulated at 1 ha resolution, based on a time-dependent Markov chain, using spatial data on forest cover composition, forest cover age, terrain, and soil. Further details of the BFOLDS model can be found in Perera et al. (2008) and at http://www.fire-regime-model.com/.

Because the location, time, intensity, and size of each fire event is generated mechanistically by BFOLDS, not subsampled from historical or other empirical distributions, all characteristics of its simulated fire regimes are entirely an emergent property of the model functions (a combination of model logic, input data, and various *a priori* assumptions). Therefore, BFOLDS is essentially an exploratory model that is well suited for investigations of what-if scenarios of weather and land cover, and subsequent examinations of spatio-temporal variability of boreal forest landscape characteristics; for example, it has been used to examine spatial potential of old growth forest occurrence (Perera et al. 2003), spatial fire regime (Perera et al. 2004), effects of climate change on land use planning (Munoz-Marquez 2005), and songbird habitat patterns under different forest cover (Rempel et al. 2007). This model also has been applied to characterize fire disturbance regimes to develop a new forest policy guide for Ontario's boreal forest (http://www.mnr.gov.on.ca/en/Business/Forests/2ColumnSubPage/STEL02_164533.html).

## Simulation assumptions and data

As with all simulation models, BFOLDS has explicit model premises and assumptions that comprise its logical foundation, as well as user-assumptions that define the specific simulation scenarios (Figure 2). In BFOLDS all simulation processes of fire events and forest cover transition are conducted at 1 ha raster resolution. Its fires can ignite if a 1 ha cell has a burnable fuel type and only while the duff moisture code (DMC) value of a 1 ha pixel is >20. Once a cell is burned, simulations assume that all fuel within that cell is consumed, and its forest cover destroyed entirely. Such a cell cannot re-burn for the next 10 years. Further details of BFOLDS model assumptions can be found in Perera et al. (2008) and at http://www.fire-regime-model.com/.

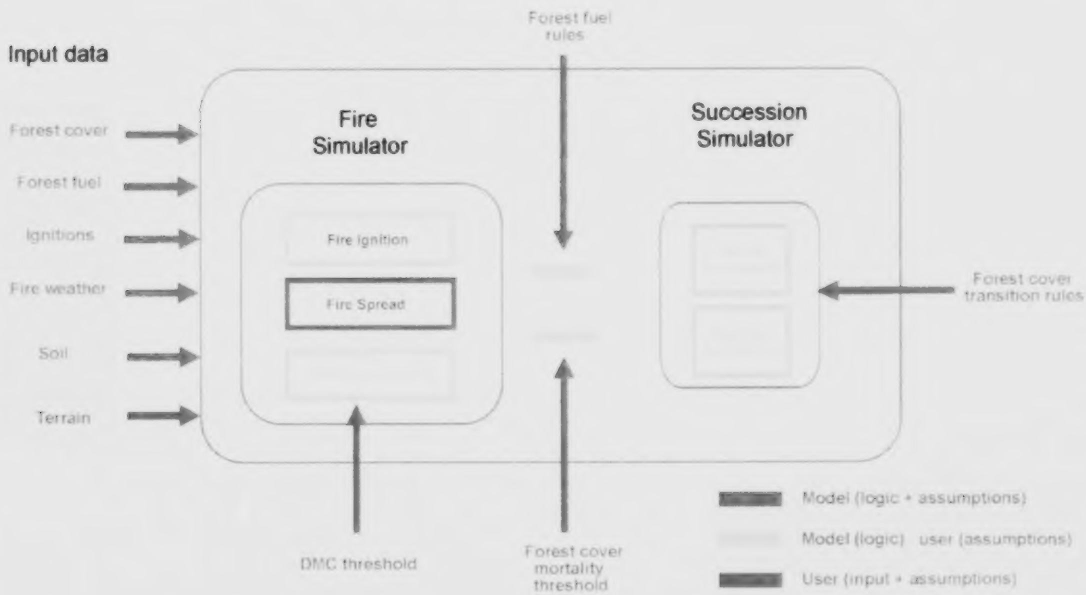


*Figure 2. A schematic overview of the Boreal Forest Landscape Dynamics Simulator, BFOLDS, indicating model assumptions, user assumptions, and input data.*

Further, for the purpose of this study, we assumed that fires spread only while the value of DMC is higher than a threshold, which varied randomly up to 10 percent during a simulation day. For ecoregions 3E and 3W, the threshold was 20±2. For ecoregions 3S, 4S, and 4W, the threshold value was 40±4 (these specific values were based on regional expert knowledge as captured in Elkie et al. 2007). Further, we assumed that a cell is deemed burned if the fire intensity was ≥150 $kWm^{-1}$, which defined a stand-replacing fire. Forest succession due to ageing in the absence of stand-replacing fires, or due to forest cover destruction by fires, were guided by ecoregional-specific forest cover transition rule sets compiled by Ride et al. (2004) for ecoregions 3W, 3S, 4S, and 4W and Vasiliauskas et al. (2004) for 3E, and subsequently modified by Elkie et al. (2007). Forest fuel classification (from forest resource inventory groupings to FBP fuel classes) followed rules specified by Forestry Canada Fire Danger Group (1992) and Taylor et al. (1988), subsequently modified for each ecoregion by Elkie et al. (2007).

In the broadest sense, input data also may be deemed as assumptions, therefore we detail the databases and their preparation in this section. All spatial datasets used in this simulation study were constructed and regionally calibrated to support the development of a new version of forest policy guidelines (http://www.mnr.gov.on.ca/en/Business/Forests/2ColumnSubPage/STEL02_164533.html) as described in Elkie et al. (2007). Table 1 summarizes all data sources used in the simulation study.

***Table 1.*** *Input data used in the simulation study and their sources. All data were used in BFOLDS as 1-ha raster surfaces.*

| Model input | Spatial data conversion | Data source |
|---|---|---|
| • Forest cover types<br>• Forest cover ages<br><br>• Fuel types | Forest Unit classification rules (Elkie et al. 2007)<br><br>Fuel classification rules of Taylor et al. (1988) and Forestry Canada Fire Danger Group (1992) as modified by Elkie et al. (2007) | 1:20,000 Forest Resources Inventory of Ontario |
| • Fine fuel moisture code<br>• Duff moisture code<br>• Drought code<br>• Initial spread index<br>• Buildup index<br>• Fire ignitions | Interpolation algorithm of Flannigan and Wotton (1989) | Daily weather data from multiple weather stations for 1963-2004 (point data) from OMNR historical fire weather archive |
| • Slope<br>• Aspect | ArcGIS functions | DTED digital elevation model (100 m) from http://geobase.ca |
| • Soil moisture<br>• Soil nutrient | Site classification rules as modified by Elkie et al. (2007) | 1:250,000 Ontario Land Inventory |

# Simulation scenarios

## Fire weather

To obtain robust estimates of characteristics of fire regime a relatively long simulation period is required. Because climate patterns may change during such a long period, we assumed three scenarios of possible changes in fire weather to explore the associated changes in fire regime. Given the uncertainty of potential changes in climate, especially at the scale of sub ecoregions at which fire simulation (and forest management planning) are conducted, we could not generate climate scenarios using a climate change model. Therefore as surrogates of potential climate change, we resorted to three simple assumptions of different fire weather scenarios – cold, normal, and warm – during simulations. The simulation scenarios were constructed from 42 years (1963-2004) of daily fire weather (temperature, relative humidity, wind, and rainfall) records from weather stations within the ecoregions. The *normal* scenario assumes that the fire weather during the 200-year simulation period unbiasedly represents the range of annual variability that prevailed during that 42-year period, i.e., each weather year was randomly selected based on probability *p* and for the *normal* scenario *p*=1/42. We then ranked the annual area burn rates for the 42 years for each ecoregion using results from the *normal* scenario, and selected the eight years with highest burn rates as the "warmest" years. For the *cold* scenario (which represents mild fire weather), we assumed that the probability of occurrence of those warmest years, $p_w$, is half the probability of the other 34 years, *p*. Because $p_w = 0.5p$ and $34p + 8p_w = 1$, we have $p = 1/38$ and $p_w = 1/76$. Similarly, for the *warm* scenario (which represents severe fire weather), we assumed that the probability of occurrence of the warmest years, $p_w$, is twice the probability of the other 34 years, *p*. Because $p_w = 2p$ and $34p + 8p_w = 1$, we have $p = 1/50$ and $p_w = 1/25$. To preserve their temporal autocorrelations, we did not alter sub-annual trends, the daily fire weather patterns within years, or hourly fire weather patterns within days.

## Fire ignition pattern

As a model assumption, the number of successful ignitions for any simulation day followed a filtered Poisson process. Poisson means are seeded by daily fire ignition values associated with fire weather input data. To account for the uncertainty of knowledge of spatial patterns of lightning-caused fire ignitions, we applied two possible scenarios of fire ignitions within ecoregions. One scenario (random) assumed that all fire ignitions within each ecoregion are randomly distributed spatially. The other scenario (biased) assumed that fire ignition occurrence is spatially biased to patterns recorded during the 42-year history of weather records (Figure 3). The seeding of fire ignitions within ecoregions was biased towards the 42-year historical pattern using the following steps.

First, we produced a raster grid of density of ignition, where density of ignition $d_i$ at cell *i* is defined as:

$$d_i = \frac{N_i}{A_i} \qquad (1)$$

where $A_i$ is the forested area of the search window (one million ha in this study) with the centre at cell *i*, and $N_i$ is the number fires that occurred during the 42-year period in the forested area of the search window. The ignition pattern is generated from the point data source based on equation (1). This resulted in the ignition density map illustrated in Figure 4.

***Figure 3.*** *Locations of lightning-caused ignitions in the study area (including the buffer area) from 1963-2004 (Source: DFOSS Fire Archive Access Database, Rob Luik, Information Management Specialist, Ministry of Natural Resources, Fire Management Section, 70 Foster Drive, Sault Ste. Marie, ON, (705) 945-6748).*

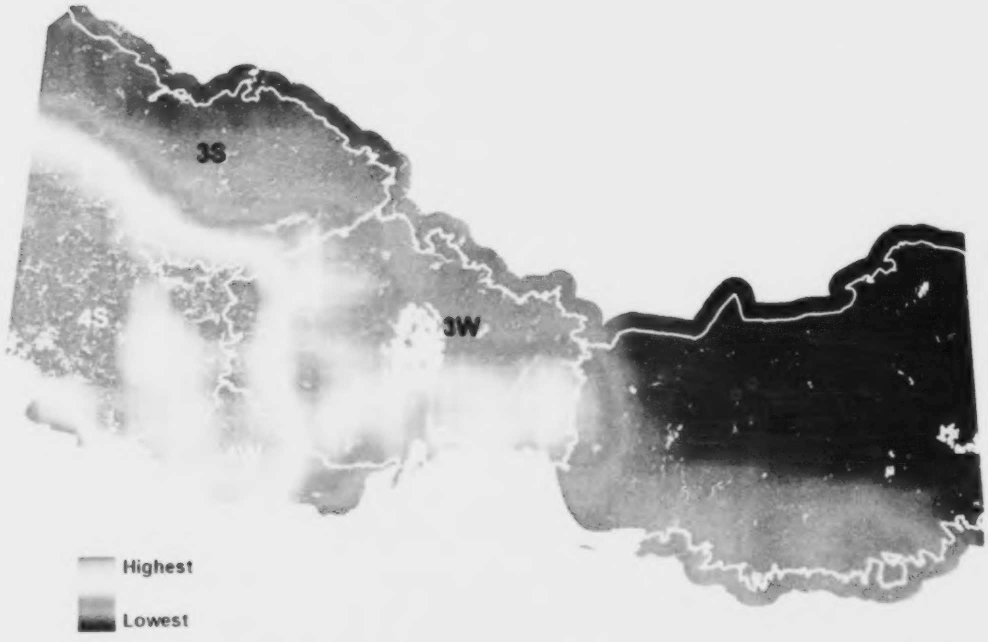


***Figure 4.*** *Ignition density map developed (see text for details) using data of lightning-caused fire locations during 1963-2004.*

**Figure 3**. Locations of lightning-caused ignitions in the study area (including the buffer area) from 1963-2004 (Source: DFOSS Fire Archive Access Database. Rob Luik. Information Management Specialist. Ministry of Natural Resources. Fire Management Section. 70 Foster Drive. Sault Ste. Marie. ON. (705) 945-6748)


**Figure 4**. Ignition density map developed (see text for details) using data of lightning-caused fire locations during 1963-2004

Second, fire locations were generated based on relative probability. This was done by randomly selecting a cell *j* (location) in the raster grid, and generating a random number *x* that ranges from 0 to 1. If *x* is smaller than $d_j$, location *j* was selected. If not, the above process (select a location, generate a random number *x* that ranges from 0 to 1, was repeated to determine if the number was smaller than the relative probability at the location) until *x* was smaller than $d_j$.

The probability of each cell *j* being selected was:

$$p_j = \frac{d_j}{\sum_{i=1}^{N} d_i} \quad (2)$$

where $p_j$ is the probability of each cell *j* being selected once, $d_j$ is the density of ignition at cell *j*, and *N* is the total number of forested cells in the study area. This generated the biased fire ignition pattern used in the study.

### Simulation study design

Altogether we conducted 900 simulation runs, each 200 years long. A 5x3x2 factorial structure was used with five ecoregions (*3E, 3W, 3S, 4S, 4W*), three fire weather (*cold, normal, warm*) scenarios and two ignition pattern (*random, biased*) scenarios. Each of the 30 simulation scenario combinations (ecoregion-fire weather-ignition) was replicated 30 times. We simulated the fire regime of the five ecoregions of the study area separately, using the present-day land cover (composition and age) of respective ecoregions as their year-zero state to seed subsequent forest succession processes. These land covers would change with time during simulations either due to ageing and/or due to fire disturbances and subsequent succession.

## Data analyses

Each fire event that occurred during the 900 simulation runs was tracked by its location and time, which permitted assemblage of many spatio-temporal summaries. To allow fires that could originate outside to spread into the study areas, we expanded the five ecoregions by imposing 20 km wide external buffers. The extents of fires within the buffers were eliminated from subsequent data analyses, regardless of their origin (study area or buffer). As well, all fires that ignited in the buffer but did not spread into the study area were not counted. For example, for the three fires shown in Figure 5, fire A spans both the study area and buffer, fire B is completely within the buffer, and fire C is completely within the study area. In this example, fire A is counted but only the portion that falls within the study area $A_i$ is included as area, $A_o$ is not; fire B is not counted; fire C is counted and all of its area included.

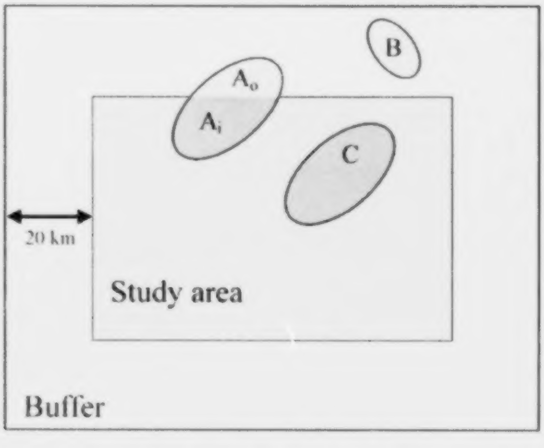


***Figure 5.*** *A hypothetical example of a study area with its buffer, illustrating the criteria defining simulated fires (number and area) included in this study.*

In this study, a forest fire is defined as a burn area starting from a single source (ignition) that falls within the study area (merged fires are counted individually), and its size is defined by the cells where fire intensity is ≥150 kW m$^{-1}$. As shown in Figure 5, the fire size of fire A is $A_i$ excluding any area where fire intensity is <150 kW m$^{-1}$. Fire that ignited but did not spread beyond 1 ha due to prevailing weather were classified as <1 ha. Fire size distribution (FSD) is defined as the probability distribution of individual fire sizes that describes the quantitative relationship between fire size and its corresponding number of occurrences in a forest landscape or region over a certain period (Cui and Perera 2008).

To examine spatial proximity patterns of forest fire, we defined two indices. One is the probability of spatial proximity (PSP) at any given location. This is defined as the probability of new fire occurrence within 200 m of that location within 20 years after its burning, including fires in same year, over a 180-year period. We estimated the probability of spatial proximity as:

$$PSP_i = \frac{n_i}{N_i} \qquad (3)$$

where $PSP_i$ is the probability of spatial proximity at cell *i*, given it burned, $N_i$ is the number of times cell *i* burns during the 180-year period, $n_i$ is the number of times that any of the neighbouring cells (within 200 m of cell *i*) burn within next 20 years. $PSP_i$ can range from 0 to 1.

The other is an aggregated index to evaluate the overall scale of spatial proximity. We defined the index as:

$$PSP_a = 100 \times \frac{n}{N}$$

where $PSP_a$ is the aggregated index, n is the total number of cells for which PSP >0 in the ecoregion, and N is the total number of forested cells in the ecoregion. The index ranges from 0 to 100.

We analyzed the significance of the different sources of variability using fixed-effects (for statistical analysis purposes, we deemed all treatments have fixed effects) factorial (5x3x2) ANOVA, with 30 replicates for each factorial combination. As well, *a priori* tests for normality (Shapiro-Wilk test) and equality of variances (Levene's test) were conducted to examine the veracity of assumptions necessary for ANOVA. Means were compared post-ANOVA with Bonferroni adjustment to maintain Type I error rate at 0.05. When individual treatment means were compared to a fixed value, we used the Bonferroni method to test the significance of difference.

# Results

## Number of fires

Number of fires simulated under different scenarios varied among ecoregions: In 3E, the fire numbers ranged from 2458 to 8110; in 3W from 7924 to 13,547; in 3S from 4592 to 8748; in 4S from 6040 to 10,377; and in 4W from 2269 to 6586. Their sizes ranged from <1 ha to maxima of 83,439 ha in 3E; 83,764 ha in 3W; 125,085 ha in 3S; 442,516 ha in 4S; and 70,317 ha in 4W.

Because of the differences in extent of forested (i.e., burnable) cover among ecoregions, we standardized the expression of fire number as density. Fire density (FD) is defined here as the number of fires that occurred per million ha of forested area in an ecoregion over a 200-year simulation period (expressed as per million ha to account for differences in extent of forested area among the five ecoregions). Simulated FD varied among ecoregions, fire weather scenarios within ecoregions, and ignition patterns within ecoregions, as well as among replicates within scenarios to different degrees (Figure 6).

Overall, ecoregion 4W had the highest simulated FD (followed by 3S, 4S, and 3W), and 3E had the lowest (Table 2). Progressively warmer fire weather scenarios (from cold to normal and from normal to warm) increased FD in all ecoregions except 3E. Random ignition patterns produced higher simulated FD in all ecoregions, most distinctly in 3S.

***Table 2.*** *Fire density per million ha (mean ± SE) under different simulation scenarios of ignition pattern and fire weather for each ecoregion. Values in bold italic are significantly (n=60; p=0.05) different from corresponding simulation scenario means within a given ecoregion.*

| Ecoregion (across ignition patterns and fire weather) | Ignition pattern (across fire weather) | | Fire weather (across ignition patterns) | | |
|---|---|---|---|---|---|
| | Random | Biased | Cold | Normal | Warm |
| 3E ***364±8*** | ***451±9*** | ***277±5*** | 307±10 | 352±12 | 441±15 |
| 3W ***1401±13*** | ***1466±18*** | ***1338±15*** | ***1257±14*** | ***1400±16*** | ***1549±17*** |
| 3S ***1847±20*** | ***2039±23*** | ***1655±18*** | ***1694±25*** | ***1790±32*** | ***2058±31*** |
| 4S ***1671±14*** | ***1785±17*** | ***1557±15*** | ***1559±18*** | ***1647±22*** | ***1807±23*** |
| 4W ***2340±38*** | ***2383±54*** | ***2299±50*** | ***1826±25*** | ***2259±26*** | ***2937±35*** |

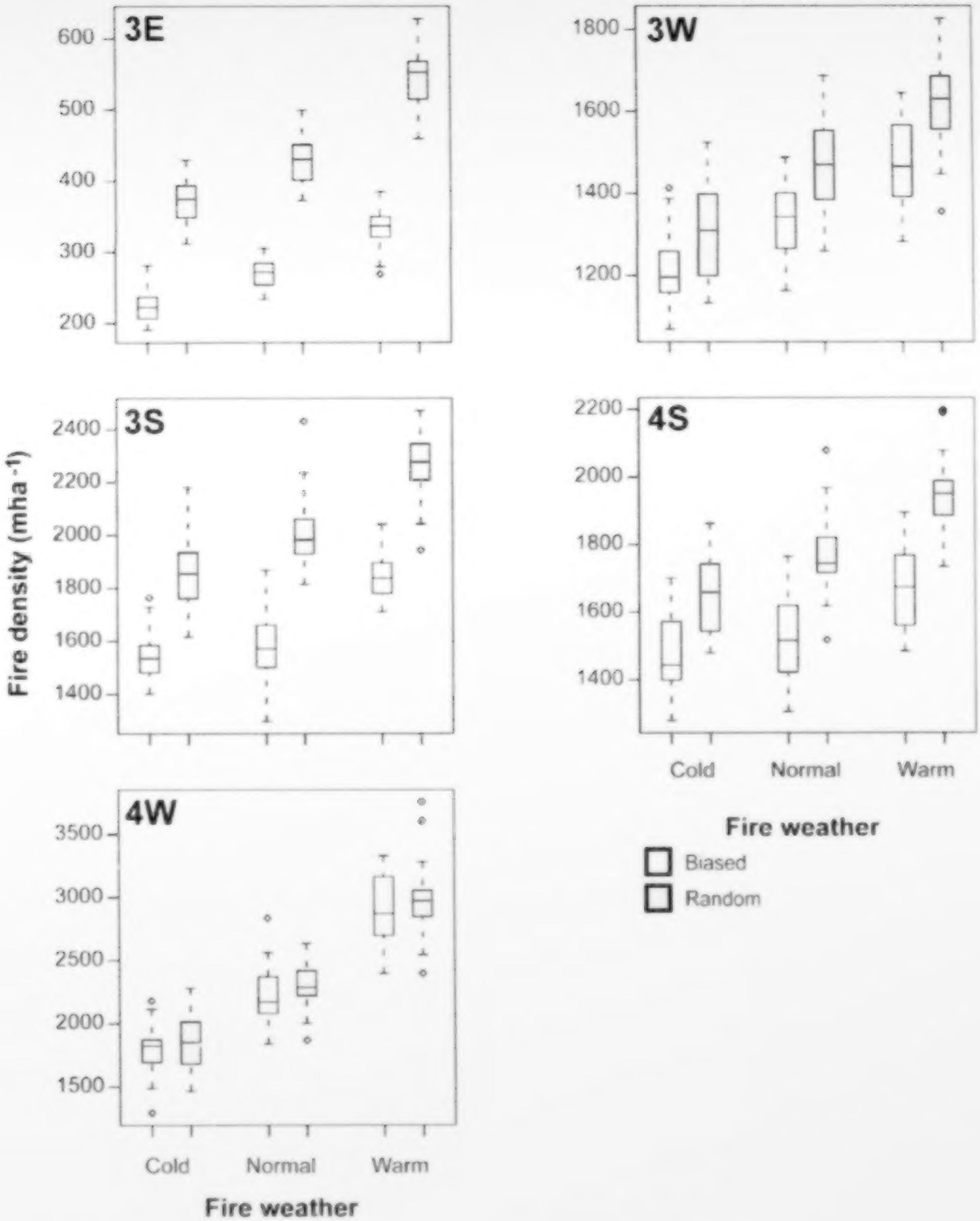


***Figure 6.** Variability of simulated fire density (number of fires per million ha) under three fire weather and two ignition pattern scenarios for five study ecoregions in boreal Ontario. Each box plot contains values from 30 simulation runs, where boxes indicate the interquartile range, middle lines the median, whiskers the min-max values, and diamonds (◊) are 1.5x interquartile range.*

## Fire size distribution

In most ecoregions, simulated fires comprised mostly very small fires that were ignited but failed to spread beyond 1 ha. These fires (<1 ha) constituted over 50% of simulated fires in ecoregions 3E (57%), 4W (61%), and 3S (61%). In Ecoregion 3W, the smallest fires contributed less (28%), and 4S had the lowest percentage of small fires (12%). To examine the overall distribution of fire sizes, we categorized the simulated fires into six size classes: <1 ha, 1-10 ha, 11-100 ha, 101-1000 ha, 1001-10,000 ha and >10,000 ha. The limits of size classes were log scale because many suggest, as reviewed by Cui and Perera (2008), that probability distributions of fire sizes are non-linear. About half of simulated fires in 4S were in the largest categories (>1000 ha), followed by 3W where the proportion of largest fires was about one fourth. Ecoregions 3E and 4W had the smallest proportion of large fires.

Table 3 summarizes the mean relative proportion (as a percentage of the total) of fires in the six size classes in the five ecoregions under the simulated fire weather scenarios. For example, in Ecoregion 3E, in the cold fire weather scenario, 59.2% of the simulated fires were <1 ha; 10.5% were between 1 and 10 ha; and 2.0% were >10,000 ha. ANOVA test showed that the effect of simulated fire weather on the proportion of fires in the size classes was significant, but varied among ecoregions. For example, proportion of fires in the smallest size class decreased with progressively warmer scenarios of fire weather (cold→normal→warm) in ecoregions 3E and 4W, but did not change in other ecoregions. Overall, the proportional fire size distribution in 4W was most responsive to fire weather scenarios and 3S the least responsive in comparison to other ecoregions.

***Table 3.*** *Number of fires in different size classes expressed as a percentage of the total (mean ± SE) under different simulation scenarios of fire weather (across ignition patterns) for each ecoregion. Values in bold italic are significantly (n=60; p=0.05) different from corresponding simulation scenario means within a given ecoregion.*

| Ecoregion | Fire weather | Percentage of number of fires in different size classes | | | | | |
|---|---|---|---|---|---|---|---|
| | | <1 ha | 1-10 ha | 11-100 ha | 101-1000 ha | 1001-10,000 ha | >10,000 ha |
| 3E | Cold | ***59.2±0.5*** | ***10.5±0.2*** | 11.7±0.1 | 10.1±0.2 | ***6.5±0.2*** | ***2.0±0.1*** |
| | Normal | ***57.3±0.5*** | ***9.2±0.1*** | 10.6±0.1 | 10.7±0.1 | ***9.3±0.2*** | ***2.8±0.1*** |
| | Warm | ***54.9±0.6*** | ***7.8±0.1*** | 9.7±0.1 | 12.0±0.2 | ***12.2±0.2*** | ***3.5±0.1*** |
| 3W | Cold | 28.8±0.2 | 10.6±0.1 | ***15.5±0.1*** | 23.6±0.1 | ***18.4±0.2*** | ***3.1±0.1*** |
| | Normal | 28.1±0.2 | 10.3±0.1 | ***14.8±0.1*** | 23.0±0.1 | ***20.1±0.1*** | 3.7±0.1 |
| | Warm | 27.3±0.2 | 10.1±0.1 | ***14.0±0.1*** | 22.6±0.1 | ***21.8±0.2*** | 4.2±0.1 |
| 3S | Cold | 60.9±0.4 | 3.7±0.1 | 7.9±0.1 | 13.3±0.1 | ***12.2±0.2*** | 2.0±0.1 |
| | Normal | 61.8±0.4 | 3.8±0.1 | 7.6±0.1 | 12.8±0.1 | 11.9±0.2 | 2.3±0.1 |
| | Warm | 61.3±0.3 | 4.0±0.1 | 7.6±0.1 | 12.6±0.1 | 11.8±0.2 | 2.6±0.1 |
| 4S | Cold | 12.5±0.1 | ***6.9±0.1*** | 12.4±0.1 | 19.2±0.1 | 29.4±0.1 | 19.6±0.2 |
| | Normal | 11.5±0.1 | ***7.5±0.1*** | 12.7±0.1 | 18.8±0.1 | 29.8±0.1 | 19.8±0.2 |
| | Warm | 10.7±0.1 | ***8.5±0.1*** | ***13.4±0.1*** | 18.4±0.1 | 29.6±0.1 | 19.4±0.2 |
| 4W | Cold | ***66.2±0.4*** | ***5.3±0.1*** | ***8.9±0.1*** | ***12.4±0.2*** | ***6.1±0.1*** | 1.2±0.1 |
| | Normal | ***61.0±0.4*** | ***5.8±0.1*** | ***9.7±0.1*** | ***15.1±0.2*** | 7.0±0.1 | 1.4±0.1 |
| | Warm | ***56.3±0.3*** | ***6.5±0.1*** | ***10.6±0.1*** | ***17.2±0.2*** | 7.1±0.1 | 1.4±0.1 |

Table 4 summarizes the mean relative proportion (as a percentage of the total) of the six size classes of fires in the five ecoregions under the simulated ignition pattern scenarios. For example, in Ecoregion 3E, for the random ignition pattern, 60.1% of the simulated fires were <1 ha; 8.5% were between 1 and 10 ha, and 2.4% were >10,000 ha. ANOVA test showed that the effect of simulated ignition patterns on the proportion of fires in the size classes was significant, but varied among ecoregions. In the smallest size class in 3E, the proportion of fires was lower under biased ignition pattern than random ignition pattern, but did not change in other ecoregions. Overall, the proportional fire size distribution in 3E was most responsive to ignition pattern change in comparison to other ecoregions.

However, while the proportionate distribution of simulated fire sizes may not appear to be responsive to different simulation scenarios, the total number of fires varied significantly with ignition pattern changes (in all ecoregions) and fire weather changes (in all ecoregions but 3E).

***Table 4.*** *Number of fires in different size classes expressed as a percentage of the total (mean ± SE) under different simulation scenarios of ignition patterns (across fire weather) for each ecoregion. Values in bold italic are significantly (n=60; p=0.05) different from corresponding simulation scenario means within a given ecoregion.*

| Ecoregion | Ignition pattern | Percentage of number of fires in different size classes | | | | | |
|---|---|---|---|---|---|---|---|
| | | <1 ha | 1-10 ha | 11-100 ha | 101-1000 ha | 1001-10,000 ha | >10,000 ha |
| 3E | Random | ***60.1±0.2*** | ***8.5±0.1*** | ***10.0±0.1*** | ***10.1±0.1*** | ***8.4±0.3*** | ***2.4±0.1*** |
| | Biased | ***53.6±0.3*** | ***9.8±0.2*** | ***11.3±0.1*** | ***11.8±0.1*** | ***10.3±0.3*** | ***3.1±0.1*** |
| 3W | Random | 28.1±0.2 | 10.3±0.1 | 14.8±0.1 | 23.1±0.1 | 20.2±0.2 | 3.6±0.1 |
| | Biased | 28.0±0.2 | 10.4±0.1 | 14.7±0.1 | 23.0±0.1 | 20.1±0.2 | 3.8±0.1 |
| 3S | Random | 61.2±0.3 | 3.8±0.1 | 7.6±0.1 | 12.8±0.1 | 12.2±0.2 | 2.4±0.1 |
| | Biased | 61.3±0.3 | 3.9±0.1 | 7.8±0.1 | 13.0±0.1 | 11.7±0.2 | 2.3±0.1 |
| 4S | Random | 11.7±0.1 | ***8.0±0.1*** | ***13.2±0.1*** | 19.0±0.1 | 29.4±0.1 | ***18.6±0.1*** |
| | Biased | 11.4±0.1 | ***7.3±0.1*** | ***12.4±0.1*** | 18.6±0.1 | 29.8±0.1 | ***20.6±0.2*** |
| 4W | Random | 61.1±0.5 | 5.8±0.1 | 9.7±0.1 | 15.2±0.3 | 6.9±0.1 | 1.3±0.1 |
| | Biased | 61.2±0.6 | 5.9±0.1 | 9.8±0.1 | 14.9±0.3 | 6.9±0.1 | 1.4±0.1 |

We examined further details of the simulated fire size distributions of the five ecoregions by estimating their 25th percentile, median, 75th percentile, and 90th percentile values (Figure 7). Small fires were so predominant in ecoregions 3E, 3S, and 4W fire sizes, even the medians of their fire size distributions were inestimable. The non-linearity of fire size distribution was evident in all ecoregions, especially in 4S and 3W.

Table 5 details the fire sizes at different percentiles of the fire size distribution under the three fire weather scenarios for each ecoregion. For example, in Ecoregion 3E, the mean fire size at the 90th percentile ranged among fire weather scenarios: from 731.5 ha (cold) to 1746.5 (normal) and 2792.4 (warm). ANOVA test showed that the effect of simulated fire weather on fire size was significant at all percentiles, but varied among ecoregions. For example, fire sizes at the 90th percentile increased with progressively warmer scenarios of fire weather (cold→normal→warm) in ecoregions 3E, 3W, and 4W, but not in 3S and 4S. Overall, the fire sizes at 75th and 90th percentiles increased with warmer fire weather in all ecoregions except 3S and 4S.

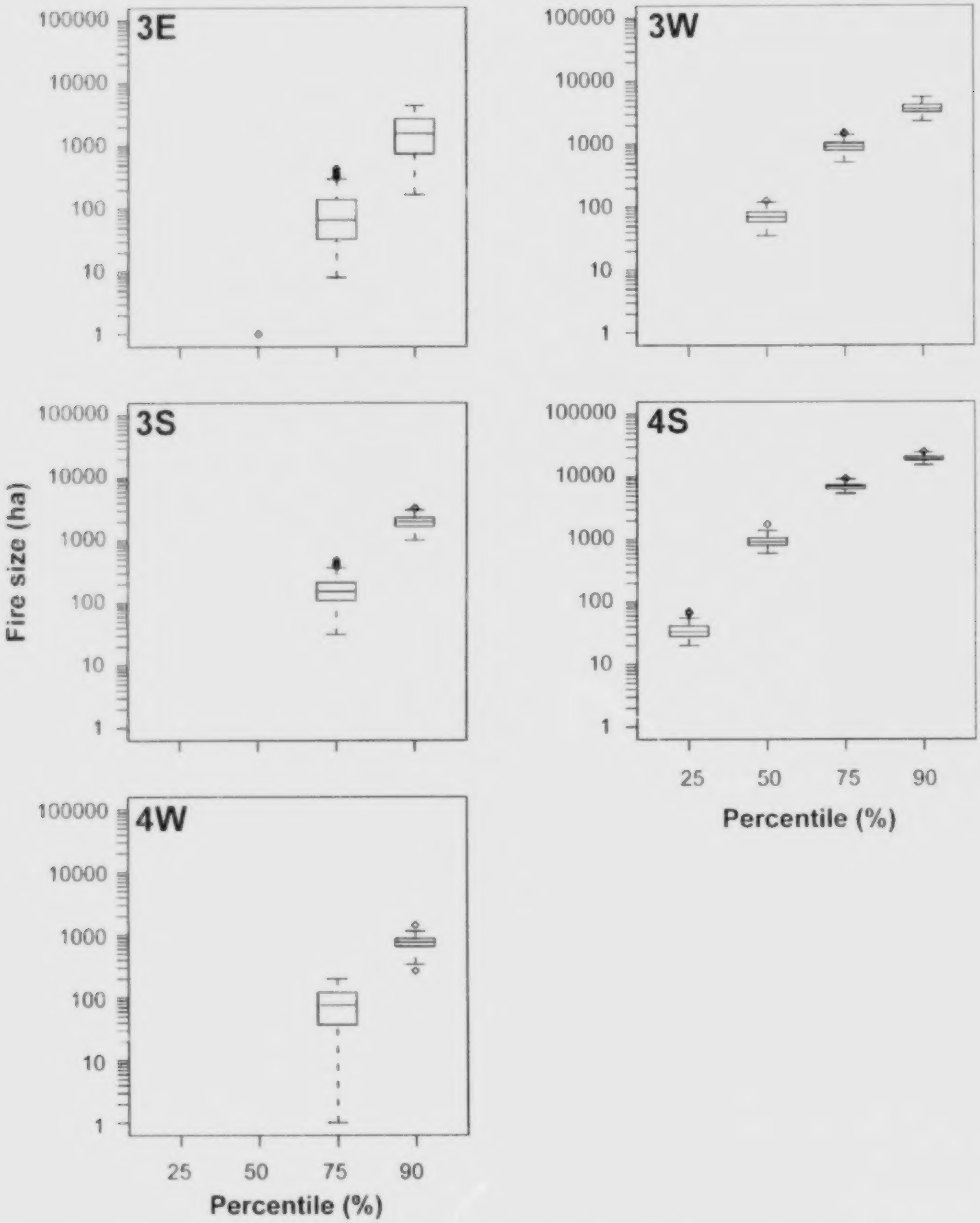


*Figure 7.* Variability in log fire size at 25th, 50th, 75th, and 90th percentiles of cumulative fire size distribution for the five study ecoregions in boreal Ontario. Each box plot contains values from 180 simulation runs, where boxes indicate the interquartile range, middle lines the median, whiskers the min-max values, and diamonds (◊) are 1.5x interquartile range.

***Table 5*** *Fire sizes at different percentiles of the fire size distribution (mean ± SE) under different simulation scenarios of fire weather (across ignition patterns) for each ecoregion. Values in bold italic are significantly (n=60; p=0.05) different from corresponding simulation scenario means within a given ecoregion.*

| Ecoregion | Fire weather | Fire size (ha) at different percentiles of cumulative fire size distribution | | | |
|---|---|---|---|---|---|
| | | 25% | 50% | 75% | 90% |
| 3E | Cold | 0.0 | 0.0 | ***35.1±3.1*** | ***731.5±68.0*** |
| | Normal | 0.0 | 0.0 | ***77.7±6.3*** | ***1746.5±99.0*** |
| | Warm | 0.0 | 0.1±0.1 | ***185.6±13.4*** | ***2792.4±107.4*** |
| 3W | Cold | 0.0 | ***58.8±1.5*** | ***735.2±12.0*** | ***3047.5±48.3*** |
| | Normal | 0.0 | ***69.6±1.8*** | ***909.0±14.4*** | ***3713.3±60.0*** |
| | Warm | 0.0 | ***85.2±2.0*** | ***1104.4±17.2*** | ***4313.2±62.8*** |
| 3S | Cold | 0.0 | 0.0 | ***174.9±11.2*** | 1954.7±60.9 |
| | Normal | 0.0 | 0.0 | 166.3±10.4 | 1992.9±63.2 |
| | Warm | 0.0 | 0.0 | 162.2±9.3 | 2004.3±55.5 |
| 4S | Cold | 35.6±1.0 | 912.7±18.3 | 6974.3±104.0 | 19520.9±263.5 |
| | Normal | 37.4±1.2 | ***978.4±27.2*** | 7127.3±123.1 | 19800.0±243.0 |
| | Warm | ***32.2±1.0*** | 916.8±22.7 | 6893.9±96.8 | 19491.8±220.4 |
| 4W | Cold | 0.0 | 0.0 | ***34.4±3.1*** | ***614.6±21.0*** |
| | Normal | 0.0 | 0.0 | ***78.7±4.0*** | ***788.1±19.6*** |
| | Warm | 0.0 | 0.0 | ***130.6±4.2*** | ***880.0±14.2*** |

Table 6 details the fire sizes at different percentiles of the fire size distribution under the two ignition pattern scenarios for each ecoregion. For example, in Ecoregion 3E, the mean fire size at the 90th percentile under random ignition pattern was 1335.1 ha and under biased ignition was 2178.5 ha. ANOVA test showed that the effect of simulated ignition patterns on the fire size was significant at all percentiles, but varied among ecoregions. In 3E and 4S biased ignition patterns produced significantly larger fires sizes, while ignition pattern had no effect on fires sizes in other ecoregions.

***Table 6.*** *Fire sizes at different percentiles of the fire size distribution (mean ± SE) under different simulation scenarios of ignition patterns (across fire weather) for each ecoregion. Values in bold italic are significantly (n=60; p=0.05) different from corresponding simulation scenario means within a given ecoregion.*

| Ecoregion | Ignition pattern | Fire size (ha) at different percentiles of cumulative fire size distribution | | | |
|---|---|---|---|---|---|
| | | 25% | 50% | 75% | 90% |
| 3E | Random | 0.0 | 0.0 | ***58.5±5.4*** | ***1335.1±88.6*** |
| | Biased | 0.0 | 0.1±0.1 | ***140.4±11.1*** | ***2178.5±124.6*** |
| 3W | Random | 0.0 | 71.0±1.8 | 909.0±19.0 | 3642.2±72.4 |
| | Biased | 0.0 | 71.4±2.0 | 923.4±21.0 | 3740.5±71.2 |
| 3S | Random | 0.0 | 0.0 | 176.6±9.2 | 2054.6±48.5 |
| | Biased | 0.0 | 0.0 | 159.0±7.4 | 1913.3±48.1 |
| 4S | Random | ***30.1±0.6*** | ***823.0±11.4*** | ***6481.3±59.4*** | ***18534.2±139.5*** |
| | Biased | ***40.0±0.9*** | ***1048.9±17.5*** | ***7515.7±79.3*** | ***20674.3±183.0*** |
| 4W | Random | 0.0 | 0.0 | 83.1±5.3 | 764.8±18.1 |
| | Biased | 0.0 | 0.0 | 79.3±5.1 | 757.0±19.9 |

## Fire size at 80th percentile

We examined fire size of 80th percentile of cumulative fire size distributions to assess specific directions in the NDPE guide (OMNR 2001). Our results showed that 260 ha did occur at the 80th percentile, but its occurrence varied among ecoregions and simulation scenarios. For example, it occurred in ecoregions 3E and 4W under certain simulation scenarios, but not in 3W, 3S, and 4S under any scenario. Table 7 shows that fire sizes at 80th percentile are significantly different from 260 ha in most simulation scenarios. It is also evident that, given the nature of fire size distribution, the magnitude of these differences are not linear, and the fire size deviation from 260 ha could be several fold even though the percentile deviation is minor (e.g., 3E, warm, biased). Conversely, Table 8 shows that occurrence of 260 ha was not significantly different from the 80th percentile under warm (random ignition) and normal (biased ignition) fire weather scenarios in 3E, and under warm fire weather regardless of the ignition pattern in 4W (follows the same trend as in Table 7). It also shows that in all other simulation scenarios in 4W, and all but one in 3E (warm fire weather–biased ignition), 260 ha occurred at percentiles *higher* than 80%. The coincident percentiles for 260 ha were much lower in 3W and in particular 4S.

***Table 7**. The fire size (ha) at the 80th percentile (mean ± SE) under different simulation scenarios of ignition pattern and fire weather for each ecoregion. Bold italicized values indicate the means are significantly different (n=30; p=0.05) from 260 ha.*

| Ecoregion | Ignition pattern | Fire weather | | |
|---|---|---|---|---|
| | | Cold | Normal | Warm |
| 3E | Random | ***56.5±3.5*** | ***124.1±10.0*** | 309.5±23.1 |
| | Biased | ***116.6±10.5*** | 281.5±21.3 | ***631.5±38.0*** |
| 3W | Random | ***1142.2±24.5*** | ***1405.4±27.9*** | ***1683.1±35.3*** |
| | Biased | ***1163.9±25.5*** | ***1429.5±32.3*** | ***1719.2±36.1*** |
| 3S | Random | ***408.5±31.7*** | ***449.5±29.7*** | ***429.4±28.3*** |
| | Biased | ***413.4±26.1*** | ***361.4±27.5*** | ***396.2±24.3*** |
| 4S | Random | ***9192.5±149.6*** | ***9154.8±134.5*** | ***8940.9±110.0*** |
| | Biased | ***10292.3±176.1*** | ***10605.6±206.4*** | ***10338.9±135.8*** |
| 4W | Random | ***108.0±8.9*** | ***175.2±9.8*** | 267.3±9.3 |
| | Biased | ***91.2±9.0*** | ***190.4±9.1*** | 251.6±7.2 |

***Table 8**. The percentiles of fire size distribution at 260 ha (mean ± SE) under different simulation scenarios of ignition pattern and fire weather for each ecoregion. Bold italicized values indicate the means are significantly different (n=30; p=0.05) from 80%.*

| Ecoregion | Ignition pattern | Fire weather | | |
|---|---|---|---|---|
| | | Cold | Normal | Warm |
| 3E | Random | ***87.8±0.3*** | ***84.0±0.4*** | 79.5±0.4 |
| | Biased | ***85.1±0.4*** | 79.9±0.4 | ***75.3±0.4*** |
| 3W | Random | ***64.1±0.3*** | ***61.8±0.3*** | ***59.7±0.3*** |
| | Biased | ***64.2±0.3*** | ***61.9±0.3*** | ***59.3±0.3*** |
| 3S | Random | ***77.6±0.5*** | ***77.2±0.4*** | ***77.5±0.4*** |
| | Biased | ***77.5±0.4*** | ***78.5±0.5*** | ***77.9±0.4*** |
| 4S | Random | ***40.1±0.2*** | ***40.1±0.2*** | ***41.0±0.2*** |
| | Biased | ***38.6±0.2*** | ***37.7±0.3*** | ***38.4±0.2*** |
| 4W | Random | ***84.9±0.3*** | ***82.6±0.3*** | 79.8±0.3 |
| | Biased | ***85.6±0.4*** | ***82.1±0.3*** | 80.3±0.2 |

## Spatial proximity of fire occurrence

We estimated the probability of spatial proximity of fires ($PSP_i$) for each 1 ha cell within an ecoregion for each replicate of simulation scenarios and derived an aggregate index ($PSP_a$) for each ecoregion based on their cell PSPs (see methods for definition and details). This PSP aggregate index shows the overall (ecoregion-level) probability of new fires occurring within 200 m of another fire within 20 years of occurrence of the latter. For a simulation replicate, $PSP_a$ can range from zero (when all cell PSPs within that ecoregion are = 0) to 100 (when none of the cell PSPs within that ecoregion is = 0). In each of the 900 simulation runs, fires did occur at least once under the spatial proximity parameters we imposed. Therefore, the aggregate $PSP_a$ was never zero in all simulation runs in all ecoregions, fire weather scenarios, and ignition patterns (Figure 8).

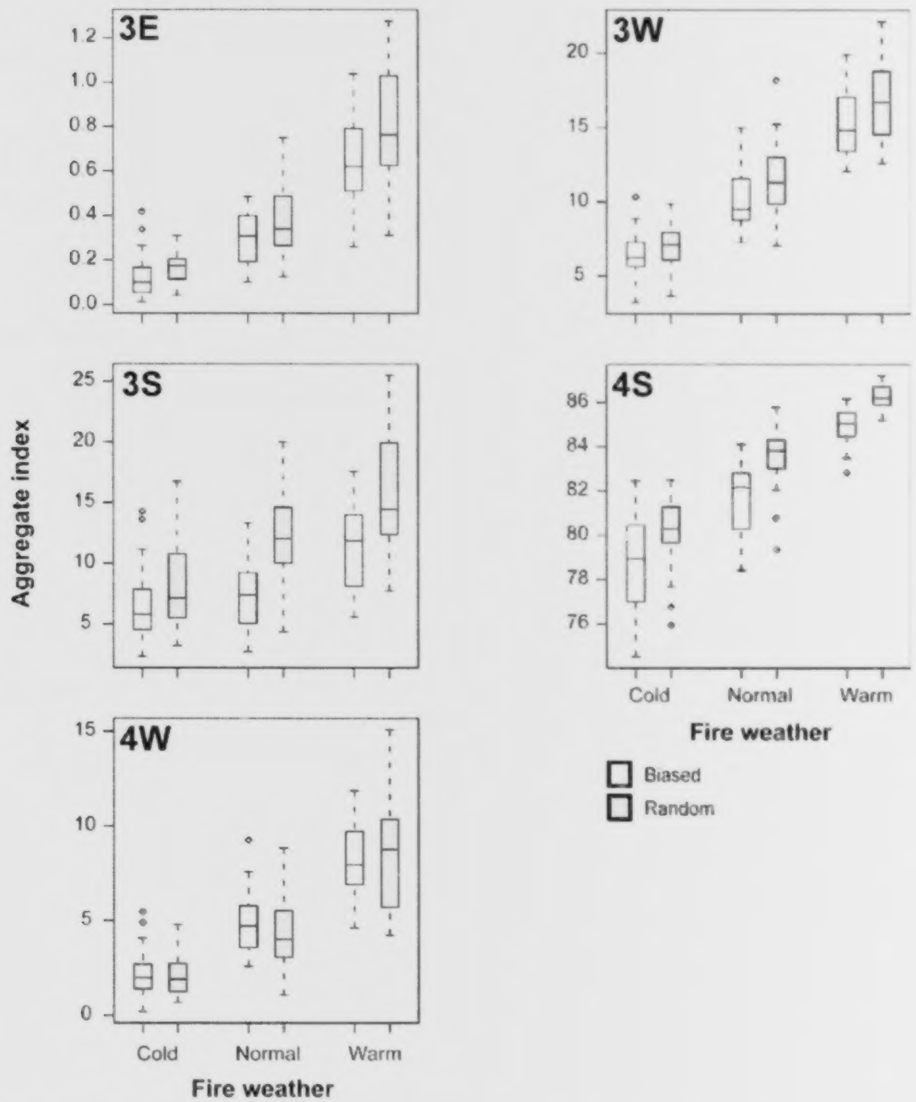


*Figure 8. Variability of the aggregate index of probability of spatial distribution ($PSP_a$) under three fire weather and two ignition pattern scenarios for five study ecoregions in boreal Ontario. Each box plot contains values from 30 simulation runs, where boxes indicate the interquartile range, middle lines the median, whiskers the min-max values, and diamonds (◊) are 1.5x interquartile range.*

However, Table 9 shows that in some ecoregions this index had very low values. ANOVA test showed that the aggregate PSP index varied significantly among ecoregions as well as fire weather scenarios but not for ignition patterns. The mean PSP index was highest in Ecoregion 4S (82.52±0.22) and lowest in 3E (0.40±0.02). In other ecoregions, mean PSP index was low: 5.00 (±0.24) in 4W, 10.22 (±0.36) in 3S, and 11.30 (±0.33) in 3W. Among simulated fire weather scenarios, colder weather produced the lowest PSP index values for ecoregions and warmer weather the highest.

***Table 9**. Mean of probability of spatial distribution (PSP) aggregate index values under different scenarios of ignition pattern and fire weather for each ecoregion. All PSP index means are significantly different (n=30; p=0.05) from 0.*

| Ecoregion | Ignition Pattern | Fire weather | | |
|---|---|---|---|---|
| | | Cold | Normal | Warm |
| 3E | Biased | 0.12±0.01 | 0.30±0.02 | 0.64±0.04 |
| | Random | 0.17±0.01 | 0.37±0.03 | 0.80±0.04 |
| 3W | Biased | 6.56±0.31 | 10.19±0.36 | 15.41±0.43 |
| | Random | 7.10±0.31 | 11.53±0.44 | 17.00±0.53 |
| 3S | Biased | 6.50±0.55 | 7.42±0.49 | 11.37±0.68 |
| | Random | 8.01±0.64 | 12.13±0.70 | 15.86±0.88 |
| 4S | Biased | 78.63±0.37 | 81.62±0.30 | 84.85±0.15 |
| | Random | 80.22±0.29 | 83.59±0.25 | 86.18±0.10 |
| 4W | Biased | 2.22±0.20 | 4.84±0.28 | 8.18±0.36 |
| | Random | 2.13±0.20 | 4.00±0.32 | 8.60±0.52 |

While $PSP_a$ index shows the overall probability of spatial proximity, it does not show how commonly fires occur in spatial proximity. To elucidate this, we categorized cell PSP values into three groups; low ($PSP_i$ = >0 - ≤0.4), medium ($PSP_i$ = >0.4 - ≤0.8), and high ($PSP_i$ = >0.8); and examined the relative proportion of these groups within ecoregions. Figures 9a-9e illustrate the proportion (as a percentage) of forested area under these groups within ecoregions under different simulation scenarios. They show that, while new fires can occur within 200 m of a <20-year-old fire, the rate of that incidence was not high in any ecoregion, with the exception of 4S. Fire weather scenarios influence these rates, but their specific effect varied among ecoregions.

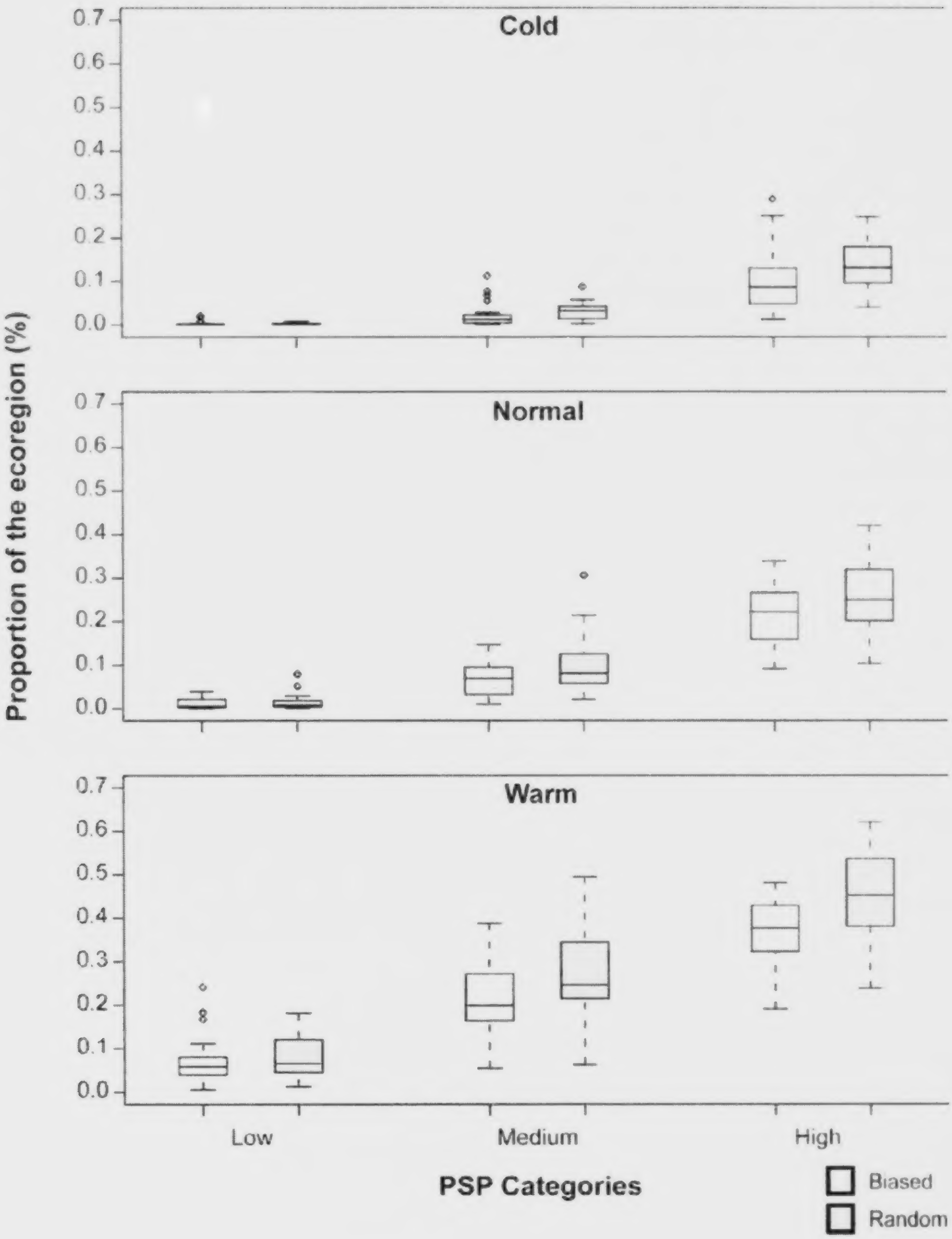


*__Figure 9a.__ Probability of fires occurring within spatial proximity limits in Ecoregion 3E for three fire weather scenarios and two ignition scenarios. Probability groupings are low ($PSP_i$ = >0 - ≤0.4), medium ($PSP_i$ = >0.4 - ≤0.8), and high ($PSP_i$ = >0.8). Each box plot contains values from 30 simulation runs, where boxes indicate the interquartile range, middle lines the median, whiskers the min-max values, and diamonds (◊) are 1.5x interquartile range.*

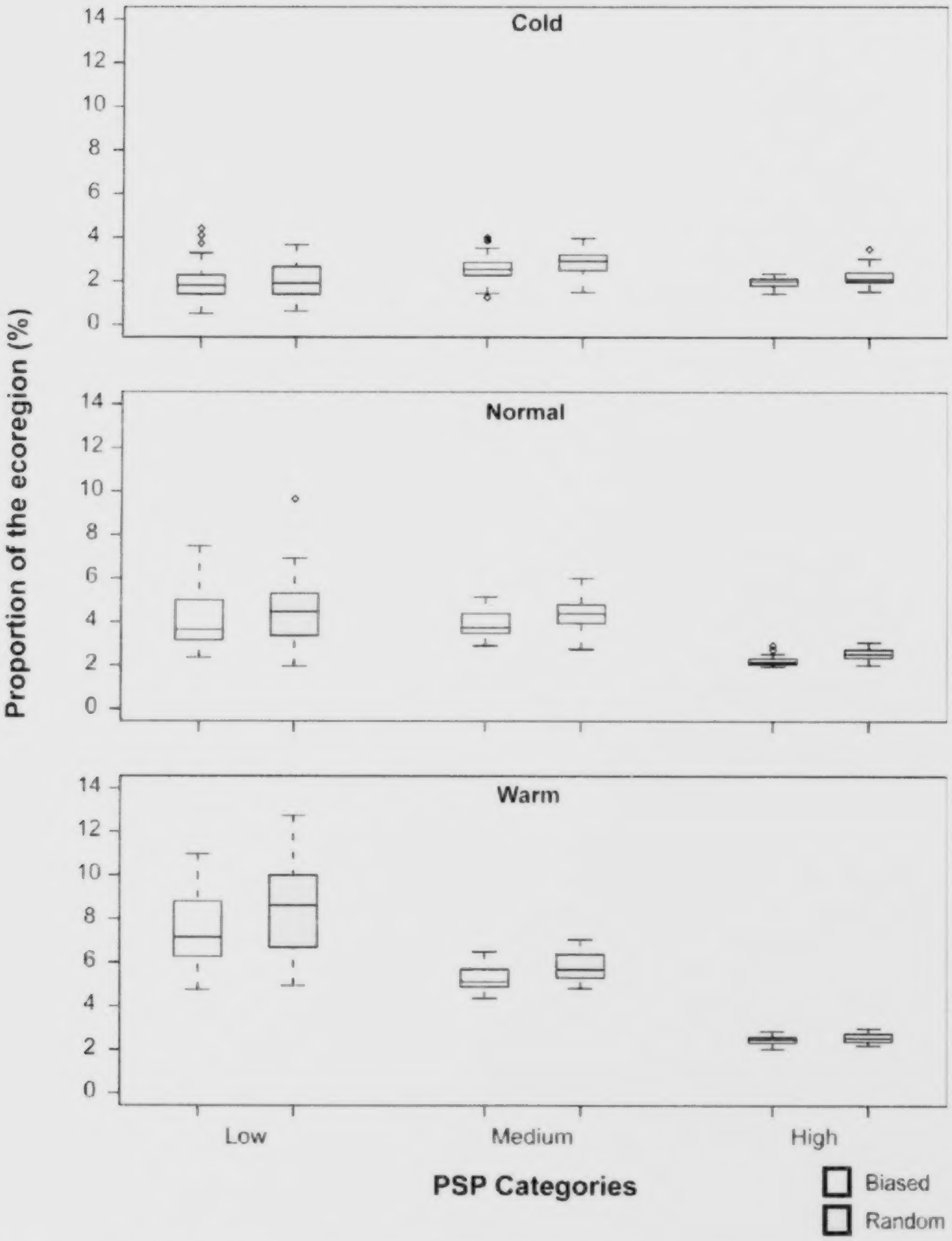


***Figure 9b.*** *Probability of fires occurring within spatial proximity limits in Ecoregion 3W for three fire weather scenarios and two ignition scenarios. Probability groupings are low (PSP = >0 - ≤0.4), medium (PSP = >0.4 - ≤0.8), and high (PSP = >0.8). Each box plot contains values from 30 simulation runs, where boxes indicate the interquartile range, middle lines the median, whiskers the min-max values, and diamonds (◊) are 1.5x interquartile range.*

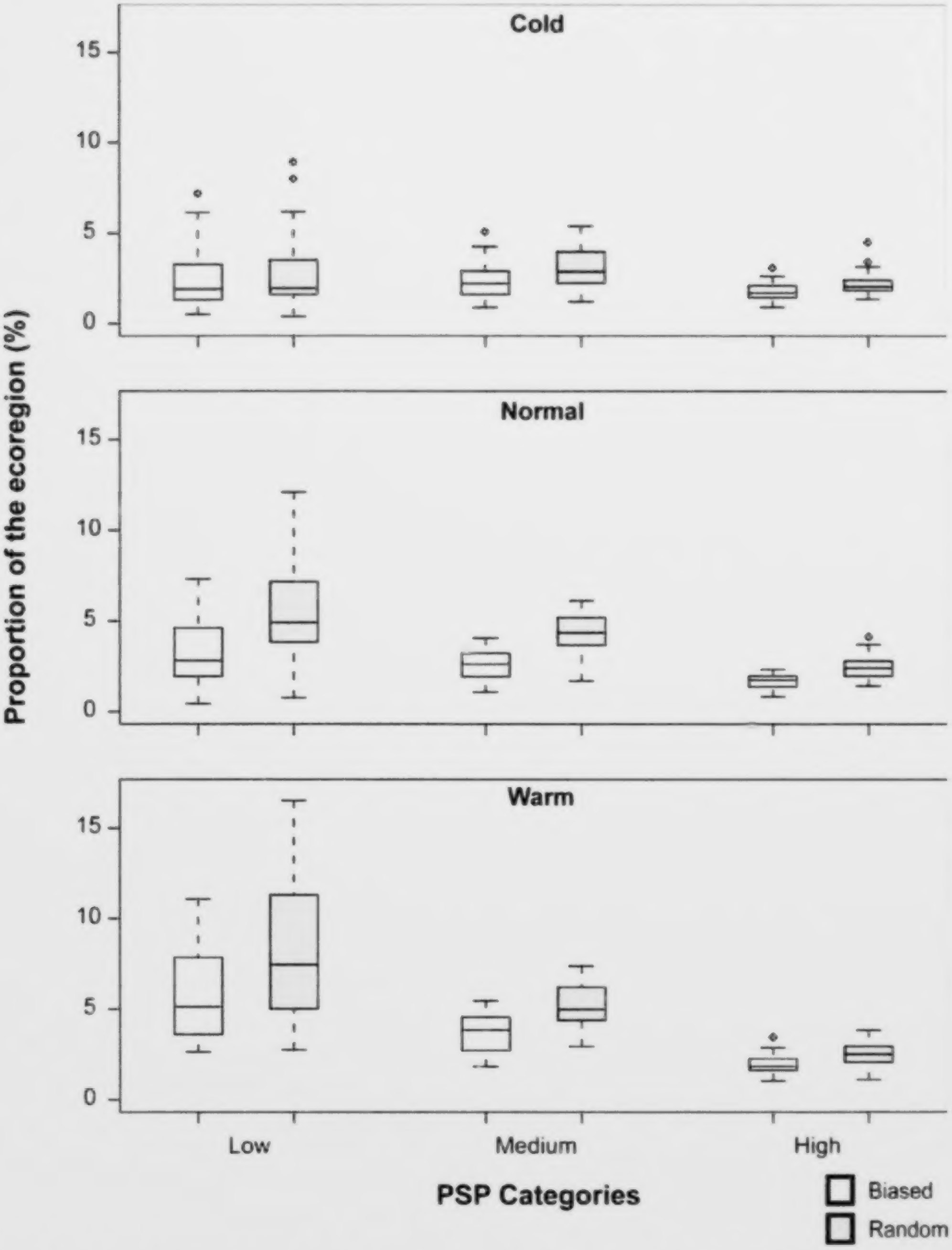


***Figure 9c.*** *Probability of fires occurring within spatial proximity limits in Ecoregion 3S for three fire weather scenarios and two ignition scenarios. Probability groupings are low (PSP = >0 - ≤0.4), medium (PSP = >0.4 - ≤0.8), and high (PSP = >0.8). Each box plot contains values from 30 simulation runs, where boxes indicate the interquartile range, middle lines the median, whiskers the min-max values, and diamonds (◊) are 1.5x interquartile range.*

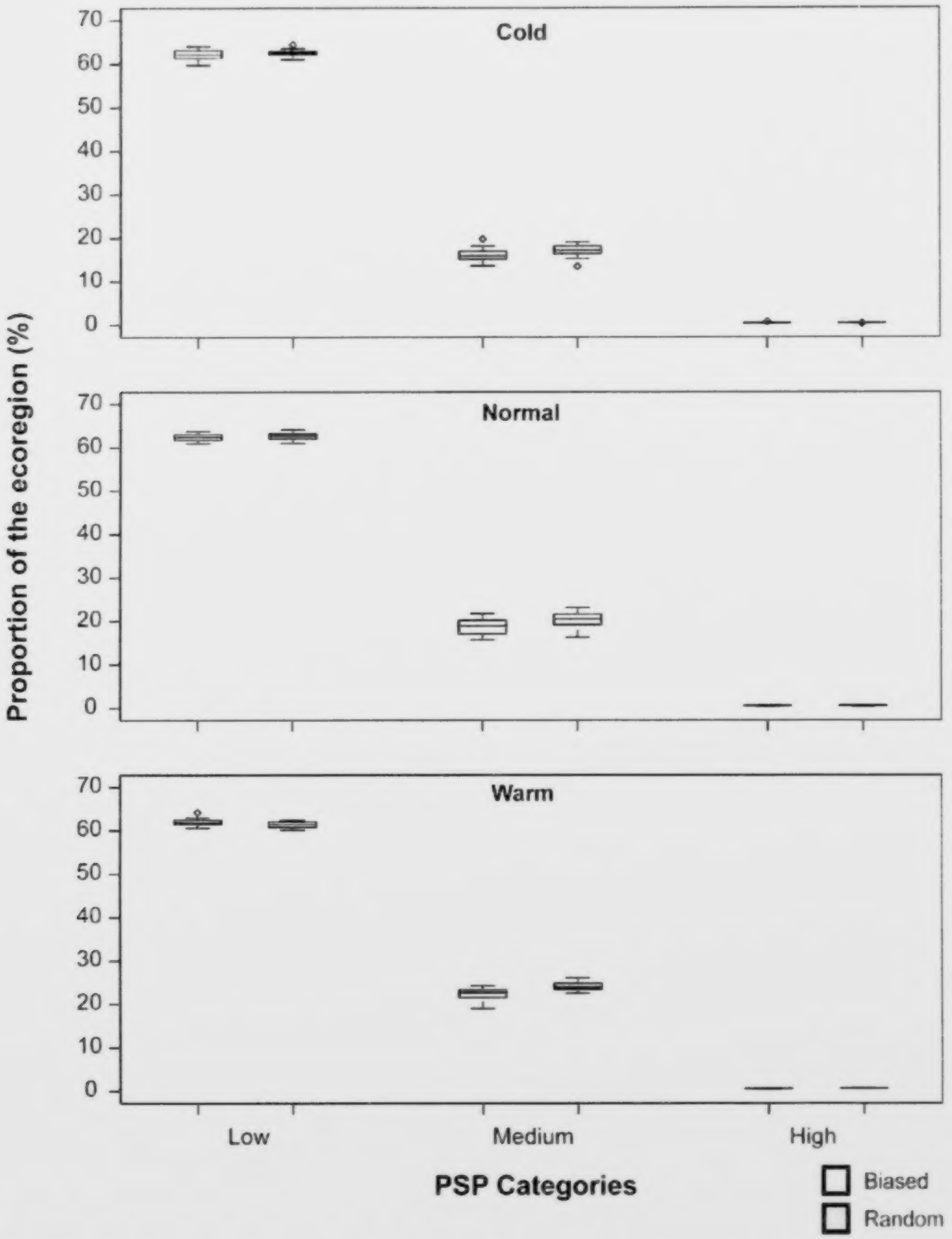


***Figure 9d.*** *Probability of fires occurring within spatial proximity limits in Ecoregion 4S for three fire weather scenarios and two ignition scenarios. Probability groupings are low ($PSP_i$ = >0 - ≤0.4), medium ($PSP_i$ = >0.4 - ≤0.8), and high ($PSP_i$ = >0.8). Each box plot contains values from 30 simulation runs, where boxes indicate the interquartile range, middle lines the median, whiskers the min-max values, and diamonds (◊) are 1.5x interquartile range.*

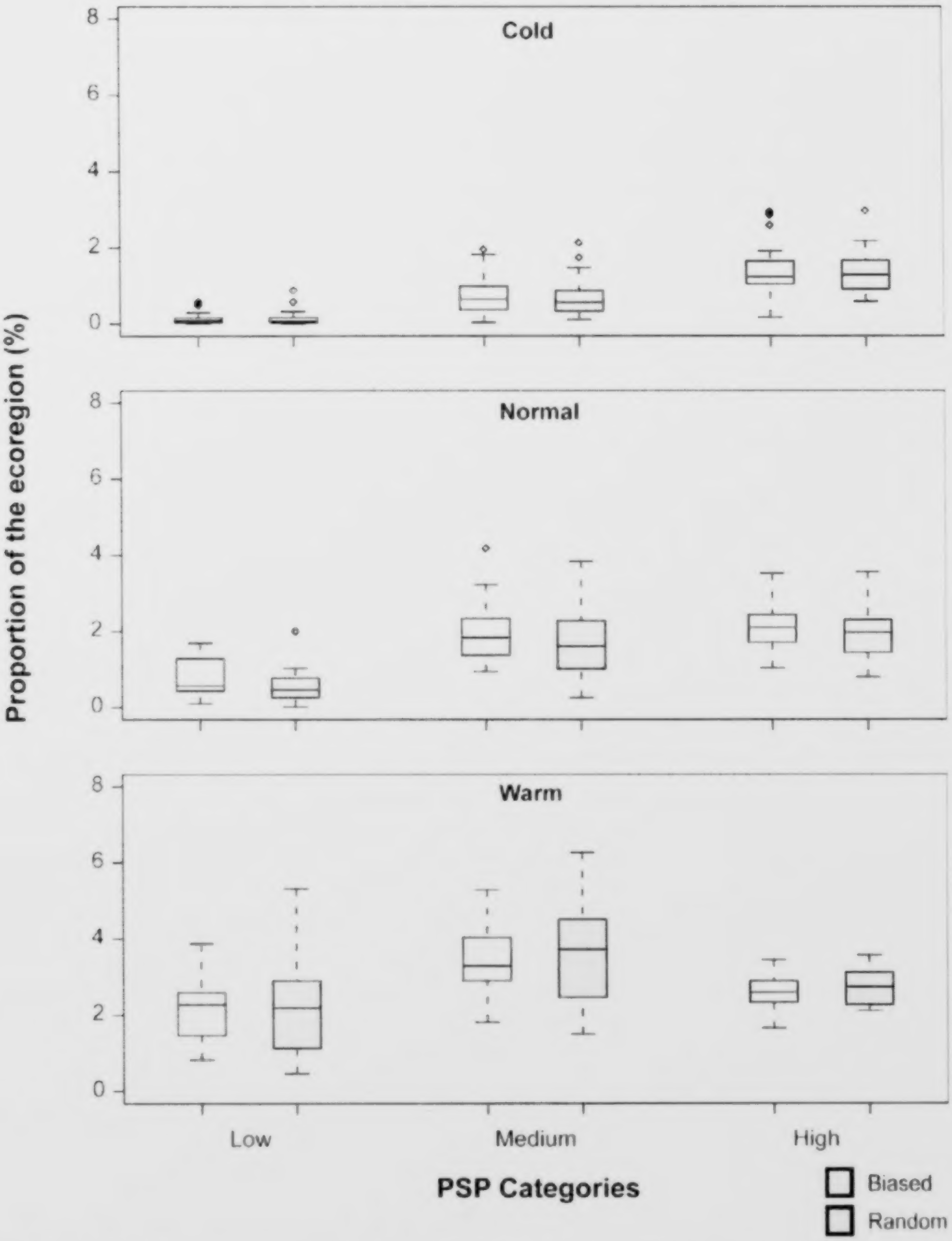


***Figure 9e**. Probability of fires occurring within spatial proximity limits in Ecoregion 4W for three fire weather scenarios and two ignition scenarios. Probability groupings are low (PSP = >0 - ≤0.4), medium (PSP = >0.4 - ≤0.8), and high (PSP = >0.8). Each box plot contains values from 30 simulation runs, where boxes indicate the interquartile range, middle lines the median, whiskers the min-max values, and diamonds (◊) are 1.5x interquartile range.*

# Discussion and Conclusions

Our goals in this section are two-fold. First, we discuss the results of our study in the context of the policy directions provided in OMNR's *Forest Management Guide for Natural Disturbance Pattern Emulation* (NDPE guide, OMNR 2001). Second, we summarize the estimates of fire size distribution and their sources of variability and implications for policy development and understanding of fire regime characteristics.

## Study results in relation to the NDPE guide directions

Below we discuss our study results in relation to the specific directions for harvest patterns provided in the NDPE guide (OMNR 2001). It states that "*... eighty percent (80% - boreal forest)... of planned new clearcuts determined by frequency... should be less than 260 ha in size.*" We examined this statement by asking the following series of questions with respect to simulated fire size distributions. Does 260 ha occur at the 80th percentile (80%) of the simulated fire size distributions? If yes, under what simulation scenarios does this occur? If not, does 260 ha occur at higher or lower percentiles, and under what specific simulation scenarios?

Simulated results showed that it does occur in two ecoregions under certain simulation scenarios (four of 30). In Ecoregion 4W, guide directions are congruent with simulated fires under warm weather regardless of ignition patterns) and in 3E under normal (biased ignition) and warm (random ignition) weather (Table 10). In the same two ecoregions, fire size of 260 ha occurs at *higher* percentiles than 80% (in 4W under cold and normal fire weather, and in 3E under cold weather). NDPE guide directions were not compatible with fires sizes in ecoregions 3W, 3S, and 4S under any weather and/or ignition patterns: under all simulations scenarios, 260 ha occurred at much *lower* percentiles than 80%. Overall, fire sizes in ecoregions 4W and 3E are either equal or are smaller than the size assumed for the 80th percentile of the fire size distribution by the NDPE guide. Conversely, ecoregions 3W, 3S, and 4S always produced fire sizes that exceed 260 ha.

The NDPE guide further states that "*New clearcuts must be separated in time from older clearcuts ...20 years..*" and "*If... the clearcut is less than 20 years old, 10-260 ha clearcuts should be separated an average 200 m (minimum 100 m)...*". We tested this statement by examining the probability of spatial proximity of simulated fires, specifically the probability of new fire occurrence within 200 m of another fire that is <20 years old. The results were not compatible with the NDPE guide direction (i.e., zero probability of spatial proximity) in any ecoregion or under any simulation scenario (Table 11). However, the probability of spatial proximity was low in all ecoregions under all simulated scenarios, except in 4S. The probability of spatial proximity was very high in that ecoregion under all simulation scenarios.

***Table 10**. Congruence of simulated fires size distribution with NDPE guide directions for different ecoregions and simulation scenarios.*

| Ecoregion | Agreement with NDPE guide: Yes (80% fires <260 ha) | No: >80% fires <260 ha | No: <80% fires <260 ha |
|---|---|---|---|
| 3E | Normal fire weather with biased ignition pattern<br><br>Warm fire weather with random ignition | Cold fire weather regardless of ignition pattern<br><br>Normal fire weather with random ignition | Warm fire weather with biased ignition |
| 3W | None | None | All fire weather and ignition patterns |
| 3S | None | None | All fire weather and ignition patterns |
| 4S | None | None | All fire weather and ignition patterns |
| 4W | Warm fire weather regardless of ignition pattern | Cold fire weather regardless of ignition pattern<br><br>Normal fire weather regardless of ignition pattern | None |

***Table 11**. Congruence of simulated fire proximity with NDPE guide directions for different ecoregions and simulation scenarios.*

| Ecoregion | Agreement with NDPE guide: Yes (zero probability of spatial proximity | No: Low probability of spatial proximity | No: High probability of spatial proximity |
|---|---|---|---|
| 3E | None | All fire weather and ignition patterns | None |
| 3W | None | All fire weather and ignition patterns | None |
| 3S | None | All fire weather and ignition patterns | None |
| 4S | None | None | All fire weather and ignition patterns |
| 4W | None | All fire weather and ignition patterns | None |

## Variability in simulated fire size distribution

Largest source of variability in simulation runs was the among-ecoregion variability. As Figure 10 illustrates, the fire size distribution (FSD) of the ecoregions as well as how they responded to different fire weather scenarios varied. In general, the FSD in ecoregions 3E, 3S, and 4W was dominated by small fires, and 3W by medium-size fires, in contrast to 4S where it was dominated by large fire sizes.

Variability added to FSD estimates due to fire weather scenarios differed among ecoregions, i.e., FSD of ecoregions responded differently to changing simulated fire weather from cold to warm. Density of fire occurrence increased with warming fire weather in most ecoregions (except 3E) and fire sizes increased in 3E, 3W, and 4W. Also, the probability of very large fires increased only within Ecoregion 3E. Overall, FSD in ecoregions 3E and 4W was most responsive to warming fire weather and in 4S was least responsive. Ignition pattern scenarios added less variability, and the effect was consistent among ecoregions: the biased ignition pattern produced fewer but larger fires than the random ignition pattern in all ecoregions. Among-replicate variability was relatively low among simulation scenarios, possibly because all FSD estimates examined here were ecoregion-level synoptic properties, masking the variability in space.

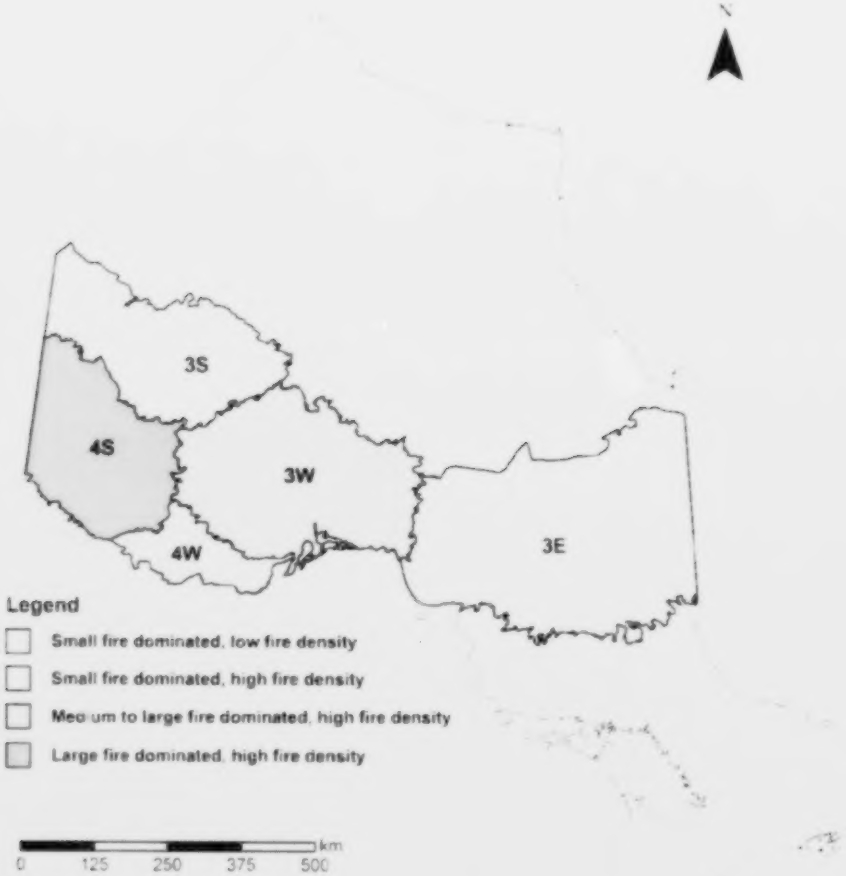


*Figure 10. Major properties of simulated fire size distribution of study ecoregions in boreal Ontario*

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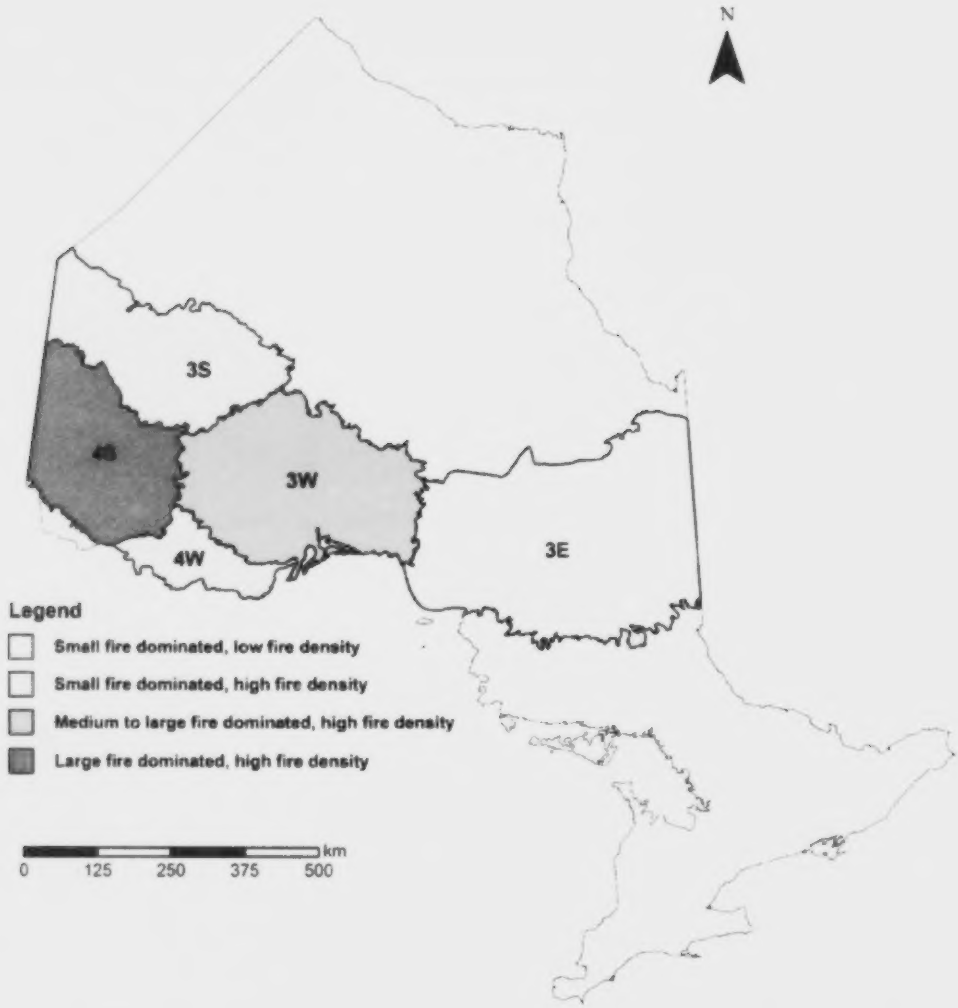


*Figure 10. Major properties of simulated fire size distribution of study ecoregions in boreal Ontario.*

It appeared that FSD is a unique spatial signature for different ecoregions, which may be a result of specific combinations of environmental conditions and anthropogenic influences within large areas, in this case ecoregions. While this agrees with overall variability among estimates of FSD reported by others, as reviewed by Cui and Perera (2008), it also presents a difficulty in directly comparing specific FSD properties derived here with those published from elsewhere. As well, the FSD responses to changes in fire weather assumptions were different among ecoregions – some (e.g., 4W) were more sensitive and others less so (e.g., 4S). This inconsistency may signal differences in the degree of robustness of FSD among ecoregions and the relative importance of specific assumptions in estimating FSD.

Variability among scenario simulations highlights two points in the context of FSDs. First, forest management policies and applications need to account for the sources and range of heterogeneity that is likely to be associated with properties of FSD. For example, the management policies and strategies could be ecoregion-specific and consider the expanded range of variability due to vagaries in fire weather. As well, the within-ecoregion variability in FSD is considerable and must not be ignored by assuming spatial homogeneity or independence in occurrence of fires and their sizes. This spatial heterogeneity among- and within- ecoregions also means that directly extrapolating estimates of fire regime characteristics to and from other geographies is not meaningful. Second, the breadth of variability associated with fire regimes cannot be readily captured from empirical data of fire histories, regardless of their popular and intuitive appeal. Even the most complete and accurate historical data is only one realization of many possible eventualities of a highly complex and stochastic ecological process – and only answers the question *what did happen*? Simulation modelling, within the context of the model logic, assumptions and input data, provides a powerful means to understand sources of variability, as well as to explore potential scenarios of fire regime to inform forest management policies, and answer the question *what could happen*? In the short term, this method will encounter difficulties that arise due to limitations in knowledge and reliance on assumptions, as well as user discomfort with its abstract approach and the large frames of spatio-temporal scale. However, in the long term, simulation modelling is likely to be a valuable tool in developing spatially explicit policies that capture the variability of fire regimes.

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